ELECTROMAGNETIC RING EXPANSION AS A HIGH-
RATE TEST: EXPERIMENTAL DEVELOPMENT

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DISCLAIMER

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We describe improvements to the electromagnetically launched expanding ring experiment that make it reproducible, analyzable, and amenable to the rapid testing of many specimens. Primary concerns are the design and containment of the solenoid, high-voltage switching of the capacitor, and electromagnetic and expansion-speed diagnostics. We demonstrate the reproducibility of the technique on carefully processed OFHC copper rings.

1. INTRODUCTION

In this paper, we discuss improvements and additions we have implemented to make the basic design pioneered by Walling and Forrestal[1] and outlined by Grady and Benson[2] amenable to quantitative analysis[3] and suitable for rapid, reproducible experiments at peak strain rates up to 10^4 s^{-1}. We consider the design of the solenoid, switching of the capacitor, measurement of the solenoid and specimen currents, and measurement of the expansion speed with a velocity interferometer (VISAR). Finally, we demonstrate the reproducibility of the experiments on carefully processed OFHC copper ring specimens.

2. EXPERIMENTAL

The experimental arrangement is shown in Fig. 1. The solenoid current, I_1, induces a counterrotating current in the specimen, I_2, and the interaction between them produces a large, uniform expansion force on the ring.[3]

2.1 Solenoid design

If the solenoid is unconstrained, it will expand along with the specimen ring,[2] not only producing a complex magnetic field at the ring, but destroying the apparatus as well. For well-characterized experiments the geometry of the solenoid must be fixed, so that time variations in the field are determined solely by variations in the solenoid current. A helical winding[2] produces a small moment on the ring, which causes it to rotate during expansion, an unacceptable

situation when one wishes to follow the motion over displacements of the order of 1 cm.

The solenoid we have designed to address these issues is shown schematically in Fig. 2. To distribute the contact load evenly, the bottoms of the winding grooves in the polycarbonate mandrel (Fig. 2a) are contoured to the radius of the wire, about 0.05 cm for the wire we commonly use. The turns are wound without pitch except in a transition strip from one turn to the next. For specimens with even very modest strength, such as lead, we have noticed no adverse effects from the magnetic field perturbation introduced
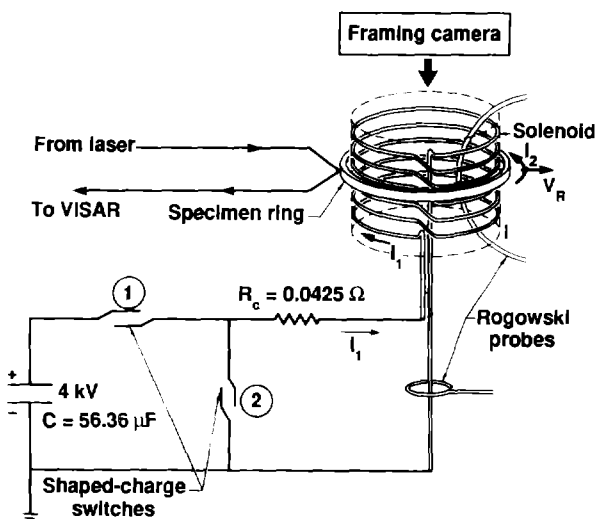

FIGURE 1
Schematic illustration of the ring expansion experiment.

by this transition. The wound solenoid is potted
in Shell Chemical Epon 828 epoxy resin with a
Union Carbide ZZL-0822 hardener to which glass
fibers have been added. Care is taken to ensure
that the epoxy fills all voids, particularly in
the transition strip, and a polycarbonate
sleeve[2] is slipped over the turns. The mandrel
is supported by a close-fitting post, and the
entire assembly is constrained by a pair of
tight-fitting polycarbonate blocks, Fig. 2b. A

(a) Solenoid mandrel design

(b) Experimental assembly

FIGURE 2
(a) Solenoid mandrel design. (b) Experimental
assembly showing placement of polycarbonate
constraining blocks.

0.1-cm-thick specimen will just fit between
turns of the solenoid while they are fully
supported by the surrounding blocks. With the
solenoid assembly thus constrained, its self-
inductance remains constant at about 1.4 μH
during the experiment and subsequent circuit
"ringdowns" used for Rogowski probe calibration.
For a capacitor voltage of 4 kV, a solenoid can
be pulsed 20-24 times before it must be retired.

2.2 Switching

If the solenoid circuit is allowed to oscil-
late during ring expansion, significant magnetic
forces may persist after the ring has attained
its maximum strain rate. But if the oscillations
are terminated when the currents are small, the
magnetic forces can be reduced to a negligible
level, considerably simplifying the constitutive
analysis. We have used shaped-charge detonator
switching for both rapid (<50-ns) initiation of
the experiment and rapid termination of the RLC
oscillations. In this technique, a small (5-mm-
diameter) shaped charge is used to penetrate a
laminate of copper foil and alternate layers of
insulating Mylar film and paper which separates
the opposite poles of the switch. A plasma is
generated which "closes" the switch, allowing
current to flow. Typical Rogowski probe records
for the time rate of change of the solenoid cur-
rent and the specimen/solenoid combined current
are shown in Fig. 3. It is clear that both the
initiation and termination occur in times less
than the digitizing interval used (50 ns). The
graph of current vs time obtained from the inte-
gration and differencing of Rogowski records
(Fig. 4, discussed subsequently) shows that the
currents remain small and undergo the expected
slow RL decay after termination. Calculations[3]
indicate that for currents of the order of 5 kA,
residual magnetic forces are negligible.

2.3 Current measurement: Rogowski probes

In order to calculate the average temperature
rise from Joule heating of the specimen and re-
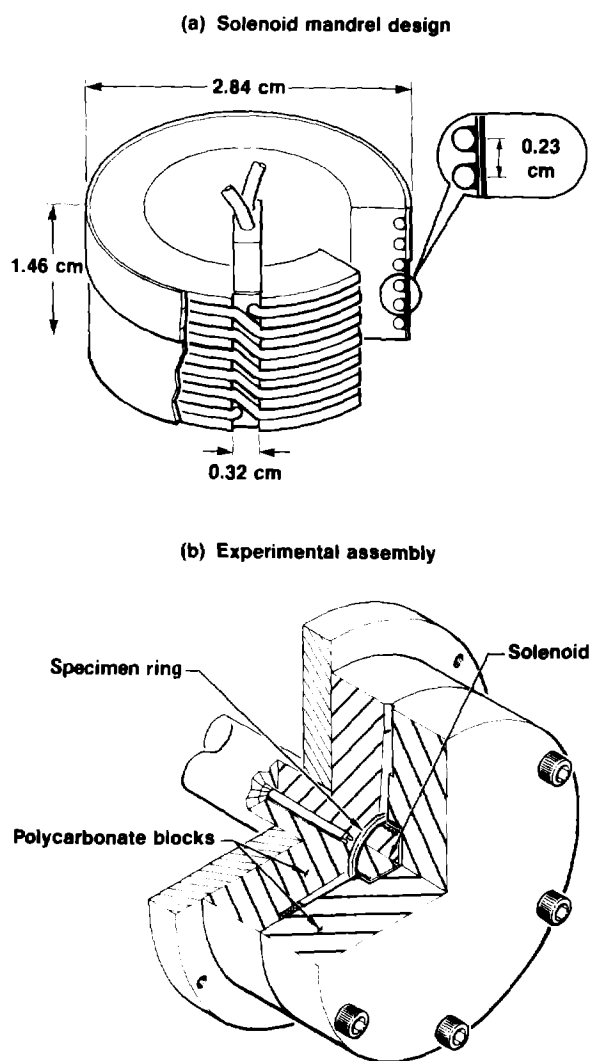move the effects of residual magnetic forces, it

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is necessary to know the currents in both the solenoid and the specimen accurately. Although the solenoid current can be measured directly with a current-viewing resistor (CVR), such a device obviously cannot be used to determine the current in the specimen ring. We have therefore adopted the method used by Walling and Forrestal[1] in which Rogowski probes are looped around one solenoid lead wire and the specimen/solenoid combination (Fig. 1). The Rogowski probe[4] produces a signal proportional to the time rate of change of the current it encloses (Fig. 3). To obtain the current, the constant of proportionality, here in units of $A/\mu s \cdot V$, must be determined by calibration against a known rate of change of current. We calibrate our probes after each experiment by analyzing the free oscillations of the solenoid. Generally the factor for a given probe varies by only about ± 0.5-1.0% from experiment to experiment with the same solenoid, and we estimate that the random uncertainty of calibration for a single experiment is ± 0.5-0.8% (2σ values). The uncertainty in the solenoid current is thus 0.5-0.8%, and that for the specimen current is 2.0-3.5%. CVR records of the solenoid current agree well with integrated Rogowski records. The average temperature from Joule heating (Fig. 4) reaches a maximum of about $150°C$, considerably larger than the estimate given in Ref. 2.

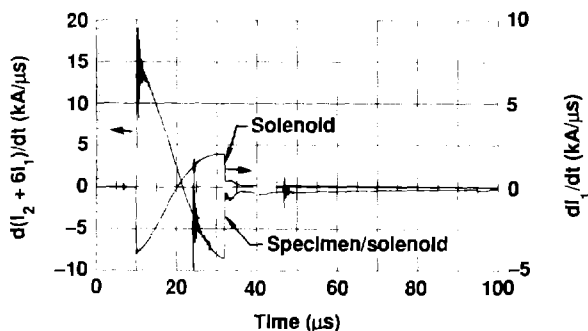FIGURE 3
Rogowski probe record for solenoid. The signal is proportional to the time rate of change for the solenoid, dI_1/dt, and the specimen/solenoid combination, $d(I_2 + 6I_1)/dt$.
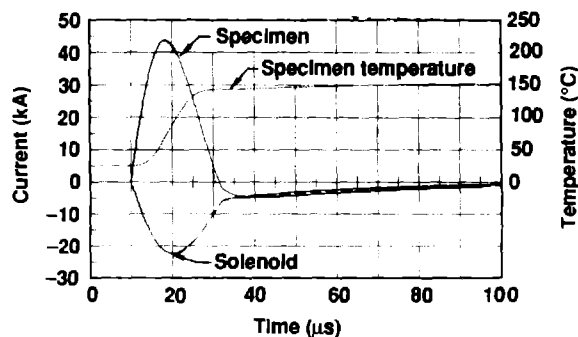

FIGURE 4
Specimen and solenoid currents obtained from the integration of Rogowski records. Note that after termination the currents remain small and undergo RL decay.

2.4 Expansion speed: VISAR analysis

Large variations in fringe offset are typical in these experiments. Figure 5a shows that the beam intensity monitor (BIM) on our three-detector VISAR[5] correctly records the qualitative changes in offset but does not exactly describe the offsets of the sine and cosine signals. We developed a simple scheme for adjusting the position of the BIM. If the sine and cosine signals have equal offset and amplitude, they will have the forms $A(t)\sin(\omega t) + I(t)$ and $A(t)\cos(\omega t) + I(t)$. The difference is

$$D(t) = A(t)[\cos(\omega t) - \sin(\omega t)]$$
$$= \sqrt{2}\, A(t)[\sin(\omega t + 3\pi/4)], \qquad (1)$$

which oscillates about 0, with extrema at $(\omega t + 3\pi/4) = \pm n\pi/2$. Because reversals are readily identified in these experiments, unambiguous values can be assigned to $(\omega t + 3\pi/4)$, and hence to ωt, at extremum times, t_{ex}. The amplitudes $A(t_{ex})$ can also be obtained, and thus, from definitions of the sine and cosine signals, the offsets $I(t_{ex})$ can be calculated. The recorded BIM signal is then adjusted to pass through these known positions. The adjustments are usually small, and the final curve provides an excellent description of the offset, yielding the normalized fringes shown in Fig. 5b. The expansion speed is calculated using the arctangent algorithm of Hemsing.[6]

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3. DISCUSSION AND CONCLUSIONS

Figure 6 shows expansion-speed profiles from several experiments on specimens of OFHC copper that had been worked 75% in each of three orthogonal directions and heat-treated for 10 minutes at 300°C to yield a final grain size of 10 μm and a hardness of about 60 kg/mm. The reproducibility is clearly excellent. From this work we conclude the following:

1. A tightly constrained solenoid, wound without pitch, is a stable and reproducible driver for magnetic ring expansion experiments.

2. Rapid switching with shaped-charge detonators is effective in initiating experiments and terminating RLC oscillations when currents are small so that the ring expands freely.
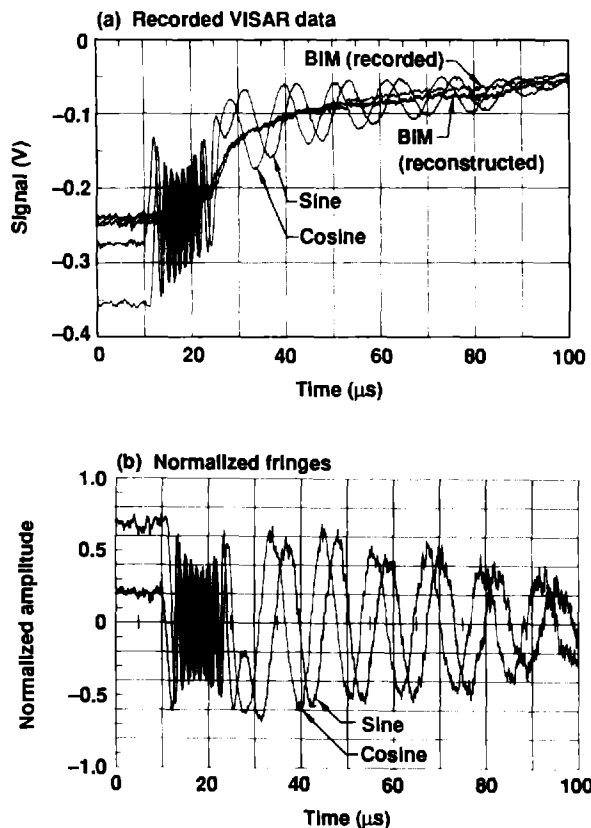
3. Rogowski probes provide an accurate means of monitoring solenoid and specimen currents.

4. The large changes in VISAR fringe intensity in these experiments can be removed using a differencing method, yielding reliable and reproducible expansion-speed records.
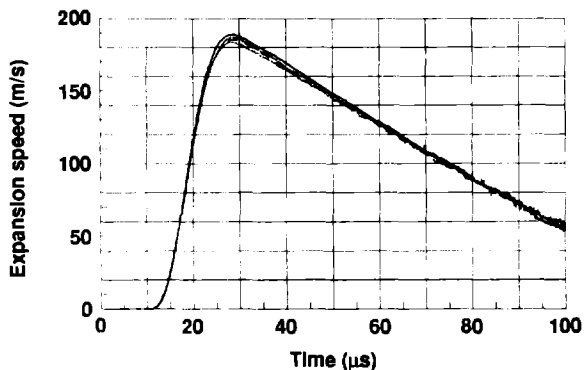

FIGURE 6
Expansion speed records for OFHC copper, 10-μm grain size.

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FIGURE 5
(a) VISAR fringes, recorded offset and adjusted offset. (b) Normalized fringes.